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Performance Analysis of a Latent Heat Thermal Energy Storage System for Solar Energy Applications

Dinu G Thomas[a], Sajith Babu C[b], Sajith Gopi[c]*

[a]*Dinu G Thomas, Student, Department of Mechanical Engineering, Government Engineering College, Kozhikode, Kozhikode, India*
E-mail : maildinugthomas@gmail.com
[b]*Sajith Babu C, Associate Professor, Department of Mechanical Engineering, Government Engineering College, Kozhikode, Kozhikode, India, E-mail : babusajith@gmail.com*
[c] *Sajith Gopi, Assistant Engineer, Kerala Water Authority, Government of Kerala, Thrissur, India,*
E-mail: sajithgopi@rediff.com

Abstract

In every solar thermal energy applications, the storage of solar energy is the most critical section of the system. To store the available solar energy at its maximum is a big challenge for the storage system. This challenge can be competed with the aid of a latent heat thermal energy storage system as it is compact and it possess high storage density. But the problem existing is cost minimization. A low cost PCM can solve this problem, from the literature survey Sodium thiosulfate pentahydrate is found to be a PCM of low cost with high latent heat of fusion and its melting point is within the desired operating environment. In order to analyze the system performance with Sodium thiosulfate pentahydrate as storage medium, the usefulness of stored energy is to be measured. But energy analysis only is inadequate to find the usefulness of stored energy. To determine this, exergy analysis based on second law of thermodynamics is required. In this work, the energy and exergy studies were experimentally done during the charging period of phase change material with a heat input of 2000W and four different mass flow rates of heat transfer fluid.

Keywords: *energy analysis; exergy analysis; phase change material; solar energy*

* Corresponding author. Tel: +919388091476
E-mail address: sajithgopi@rediff.com

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Nomenclature

A	cross sectional area at outlet section of storage tank	m^2
d	inner diameter of storage tank	m
D	outer diameter of storage tank	m
g	acceleration due to gravity	m/s^2
k	thermal conductivity of HTF	W/m K
L	length of storage tank	m
$\dot{m}$	mass flow rate of HTF	kg/s
V	velocity of HTF at outlet section of the storage tank	m/s
C_{HTF}	specific heat capacity of HTF	J/kg K
C_{PCM}	specific heat capacity of PCM	J/kg K
Ex	exergy	J
Gr_D	Grashof's number based on outside diameter	
h_i	inside heat transfer coefficient	W/m^2
h_o	outside heat transfer coefficient	W/m^2
k_{PVC}	thermal conductivity of PVC	W/m K
Nu_d	Nusselt number based on inside diameter	
Nu_D	Nusselt number based on outside diameter	
Pr	Prandtl number	
Re_d	Reynolds number based on inside diameter	
r_i	inner radius of storage tank	m
r_o	outer radius of storage tank	m
T_e	environmental temperature	K
T_f	film temperature	K
$T_{HTF,in}$	inlet temperature of HTF	K
$T_{HTF,out}$	outlet temperature of HTF	K
T_m	mean temperature of HTF in storage tank	K
T_{PCM}	melting point of PCM	K
$T_{PCM,final}$	final temperature of PCM	K
$T_{PCM,in}$	initial temperature of PCM	K
Ts	outer surface temperature of storage tank	K
μ	absolute viscosity	Ns/m2
ν	kinematic viscosity	m2/s
β	volumetric thermal expansion coefficient	K-1
Ψ	exergy efficiency	
ρ	density of HTF	kg/m3

1. Introduction

In the today's world situation of growing energy crisis, renewable energy sources stands as the only possibility. Even among that, solar energy is considered to be the best because of its cheap availability and cheaper means of tapping. For the consistent utilization of this, storing is essential because its availability is intermittent. Sensible heat storage, latent heat storage and thermo-chemical storage are the various practices of storing solar energy. Latent heat storage has advantages over other methods because it is compact, economically viable and stores or retrieves heat at uniform rates. It can store 5-14 times more heat per unit volume than sensible heat storage materials, Phase change materials (PCM) are commonly used as latent heat storage medium. A list of phase change materials and its selection criteria to use it as a latent heat storage system was defined by Sharma *et al.* [1] in the review about thermal energy storage with phase change materials and applications in 2009. By considering the melting point of preferred applications, phase change materials are selected which is highly attainable in wide ranges with different melting points. In this work Sodium thiosulfate pentahydrate is selected as phase change material. In order to analyze the system performance with Sodium thiosulfate pentahydrate as storage medium, the usefulness of stored energy is to be measured. But energy analysis only is inadequate to find the quality of stored energy. To determine this, exergy analysis based on second law of thermodynamics is required. The need for performance analysis was well defined by Jegadheeswaran *et al.* in 2010 [2] in the review, Exergy based performance evaluation of latent heat thermal storage system

In this work, a latent heat thermal energy storage system (LHTES) was developed and its performance was analyzed experimentally on the basis of energy analysis and exergy analysis. From the literature survey, the temperature of the air coming out from a solar collector has a temperature about 60ºC to 70ºC. With an electric heater the air (which was used as the heat transfer fluid in this work) was heated to this much amount.

1.1. Energy Analysis

In order to evaluate the performance of an LHTES unit its effectiveness or efficiency is to be determined. The efficiency or effectiveness of a LHTES shows how effectively the heat is stored or recovered in it. Kaizawa *et al.* [3] have used the energy efficiency as

$$\eta = \frac{Total\ heat\ stored\ in\ the\ unit}{Maximum\ heat\ storage\ capacity\ of\ the\ unit}$$

The energy analysis shows the various parameters that influences the efficiency of LHTES unit. But it only focuses on ways to improve the quantity of heat stored or recovered, but the usefulness of this stored energy could not be obtained. To determine this, exergy analysis based on second law is required. Thus for an optimized LHTES system exergy analysis is required. This is because the degradation of energy stored or recovered is very well defined in second law analysis and also the cause of irreversibilities can also be find using second law analysis.

1.2. Exergy Analysis

When a system undergoes a process, the maximum work that can be produced by the system as it comes to equilibrium with the surroundings is called exergy. Exergy quantifies the quality (usefulness) of energy. As the state of the system deviates more from its surroundings, the exergy become more when system and surroundings attains equilibrium, the exergy becomes zero. Thus it is possible to say that unlike energy, exergy cannot be conserved, but can be consumed or destroyed. In case of LHTES system, the exergy analysis is more beneficial than energy analysis, because LHTES units are used to store useful work. Since a LHTES unit is concerned only with heat transfer, the exergy depends on the temperature at which it is available in relation to the temperature of surroundings. Jegadheeswaran *et al*. [2] defined the exergy efficiency as,

$$\Psi = 1 - \frac{Exergy\ destroyed}{Exergy\ input}$$

Dermizel and Ozlmik in 2006 [4] included the following expression for the rate of exergy supplied by the HTF during charging period,

$$Exergy, in = \dot{m}C_{HTF}\left[(T_{HTF,in} - T_{HTF,out}) - \left(T_e ln\left(\frac{T_{HTF,in}}{T_e}\right)\right)\right]$$

The rate of exergy stored in PCM is given as,

$$Exergy\ stored = Q * \left(1 - \frac{T_s}{T_{pcm}}\right)$$

Where, Q is the heat gained by PCM and can be obtained from the energy balance equations. That is

$$\text{Heat gained by PCM} = \text{Heat transferred by HTF}$$

Heat transferred by HTF, $Q = \dot{m}_{HTF}C_{HTF}(T_{HTF,in}-T_{HTF,out})$

2. Experimental Setup

A latent heat thermal energy storage system is developed with Sodium Thiosulfate Pentahydrate as the phase change material for heat storage. 2.75kg of the storage material was used. In order to enhance the heat transfer between the heat transfer fluid (HTF) and the storage medium the storage material was equally distributed in aluminium tubes. All these tubes are arranged parallel with the flow of heat transfer fluid. This arrangement will increase the contact surface area of storage material and heat transfer fluid. All these tubes are kept within a PVC pipe, which is used as the storage tank. From the literature survey, it was found that the air coming out through the surface of a flat plate solar collector will be at a temperature in between 60^0C-70^0C. In order to make the temperature of air to this much amount, a 1500W electric heater was developed. The inlet section and exit section of the storage unit was made conical in shape in order to make the flow of heat transfer fluid uniform within the storage tank. The performance evaluation of this developed system was done for four different mass flow rates of heat transfer fluid. The flow rates of heat transfer fluid used were 0.01kg/s, 0.015kg/s, 0.02kg/s and 0.0225kg/s on the basis of both energy analysis and exergy analysis. The mass flow rate of air is given by the equation,

$$\dot{m} = \rho AV \tag{1}$$

The schematic representation of the experimental setup is shown in figure 1 and the developed experimental setup in figure 2. From the above equation, the air velocity at exit of the storage tank for the required mass flow rates were calculated and tabulated as shown in table 1. The dimmer stat in the blower was adjusted so that it gives the desired air velocity. The velocity of air was measured using an anemometer placed at exit of the storage tank. The heater was made on. The hot air was allowed to pass through the PCM storage tank. The temperature of the air at inlet and exit section of the storage tank is noted from the thermocouple reading. Minerally insulated k-type thermocouples were used and all these are connected to the data logger connected with the computer. The temperature of PCM at different positions of storage tank is noted and its mean value was calculated. The temperature at the outer surface of the PVC tank is noted for the calculating the heat loss through the surface. All the thermocouples readings are noted for every one minute.

Table 1. Velocity for required flow rates

Mass flow rate of air, in kg/s	Required air velocity at exit of the storage tank in m/s
0.01	9
0.015	13.5
0.02	18.5
0.0225	20.5

For the performance analysis of the developed system, energy analysis and exergy analysis have to be done. The energy efficiency of the storage system can be determined using the following method.

$$\text{Energy efficiency} = \frac{\text{Energy in} - \text{Energy loss}}{\text{Energy in}} \tag{2}$$

$$\text{Energy in} = \dot{m}C_{HTF}\left(T_{HTF,in} - T_{HTF,out}\right) \tag{3}$$

Energy Loss = energy loss due to internal forced convection + energy loss due to conduction through PVC wall + energy loss due to natural convection from surface of the storage tank.

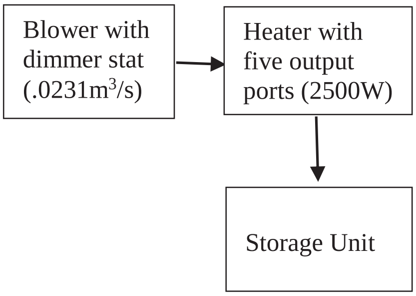

Fig. 1. schematic representation of the experimental setup

Fig. 2. experimental setup

In order to find internal convection resistance ($1/2\pi L h_i r_i$), the inside heat transfer coefficient has to be identified. The flow was turbulent and the L/D ratio was below 10. Thus the correlation for calculating Nusselt number at the entrance region of the flow should be used to obtain the internal heat transfer coefficient(h_i)

$$Nu_d = 0.036 Re_d^{0.8} Pr^{0.33} (d/L)^{0.055} \quad (4)$$

$$Re_d = \frac{ud}{v} \quad (5)$$

u is the velocity of HTF in the storage tank, can be determined from the equation, $u = \frac{AV}{a}$ (A – cross sectional area at outlet section of the storage tank, V – velocity of HTF at its outlet section and a is the cross sectional area of the storage tank)

The properties of air for the calculations are taken at mean temperature,

$$T_m = \frac{T_{HTF,in} + T_{HTF,out}}{2} \quad (6)$$

$$Nu_d = \frac{h_i d}{k} \quad (7)$$

From this equation the value of internal convective heat transfer coefficient (h_i) can be obtained.

Energy loss due to natural convection from outer surface of the storage tank can be determined by the following correlations

$$Nu_D = \left\{ 0.60 + 0.387 \left[\frac{Gr_D \, Pr}{\left\{ 1 + \left(\frac{0.559}{Pr} \right)^{0.5625} \right\}^{0.296}} \right]^{0.167} \right\}^2 \quad (8)$$

$$Gr_D = \frac{g \beta \Delta T D^3 \rho^2}{\mu^2} \quad (9)$$

$$\beta = \frac{1}{T_f} \quad (10)$$

$$T_f = \frac{T_s + T_a}{2} \quad (11)$$

$$Nu_D = \frac{h_o D}{k} \tag{12}$$

From this equation the value of natural heat transfer coefficient at outer surface of the storage tank can be obtained.

And the conduction resistance through the PVC can be determined from the equation,

$$R_{cond} = \frac{\ln(\frac{r_o}{r_i})}{2\pi k_{PVC} L} \tag{13}$$

Thus the total resistance R_{total} can be find using the following equation

$$R_{total} = \frac{1}{2\pi L}\left(\frac{1}{h_i r_i} + \frac{1}{k_{PVC}}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_o r_o}\right) \tag{14}$$

and

$$Q_{loss} = \frac{T_m - T_e}{R_{total}} \tag{15}$$

From these equations energy efficiency was calculated

Like this

$$\text{Exergy efficiency} = \frac{\text{Exergy stored}}{\text{Exergy in}} \tag{16}$$

$$\text{Exergy stored} = \text{Energy stored} * \left(1 - \frac{T_e}{T_{pcm}}\right) \tag{17}$$

$$\text{Energy stored} = \text{Energy in} - \text{Energy Loss} \tag{18}$$

Exergy input is the exergy content associated with the heat transfer fluid and is given by

$$\text{Exergy, in} = \dot{m}C_{HTF}\left[(T_{HTF,in} - T_e) - \left(T_e \ln\left(\frac{T_{HTF,in}}{T_e}\right)\right)\right] \tag{19}$$

3. Results and Discussions

The experiment has been performed for four different mass flow rates of heat transfer fluid during the charging time of PCM. The variation of inlet temperature of heat transfer fluid and temperature of phase change material with time is shown in figure 3. By analyzing the graph, the following conclusions can be made,

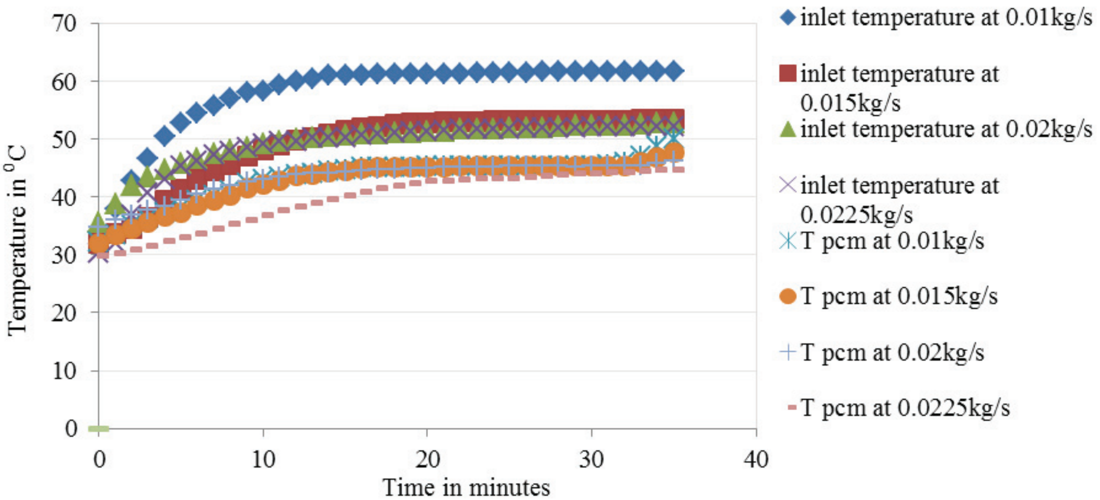

Fig. 3. variation of inlet temperature of htf and temperature of pcm with time

- The plot of temperature variation shows that the temperature of the HTF increases with a time at first and then becomes steady.
- The phase change takes place at a temperature of 45.28°C.
- The temperature of the PCM increased from 30°C to 45.28°C, then it became steady and then increased to 50°C which shows the sensible heating process before and after the latent heating.
- At a flow rate of 0.01kg/s phase change took place at 15minutes but when flow rate was increased to 0.0225kg/s, the melting started after 30 minutes.
- For lower flow rates, the temperature of the HTF increases quickly. Thus the phase change takes place quicker. For higher flow rates the temperature of HTF increases slowly, thus melting of PCM takes place slowly.

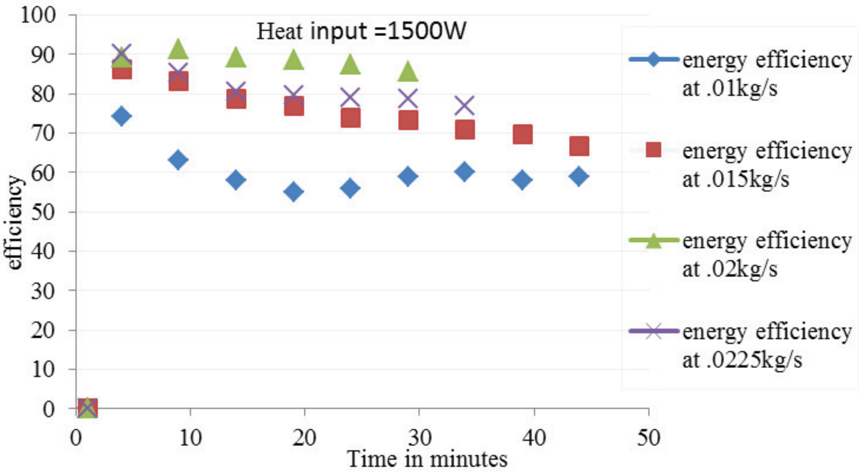

Fig. 4. variation of energy efficiency

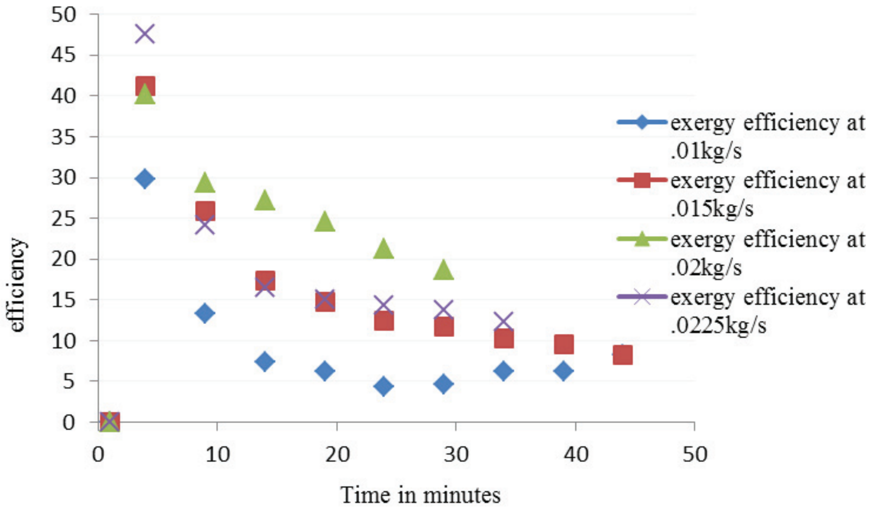

Fig. 5. variation of exergy efficiency

The variation of energy efficiency and exergy efficiency of the developed storage system for a heat flux of 1500W at the four different mass flow rates of heat transfer fluid with time is plotted below in figure 4 and figure 5.

The variation of energy and exergy efficiency against time shows a decreasing trend for all flow rates. The flow rate of 0.02kg/s was found to be the best. This is because at lower flow rates of 0.01kg/s and 0.015kg/s, the heat transfer fluid was heated much more which boosted the loss through the surface of the storage tank. Thus the energy efficiency decreases. Along with this, due to the increase in temperature of the heat transfer fluid with time, the entropy generation within the system also increases. The exergy loss is proportional to entropy generation. Thus the exergy efficiency of the system decreases as time goes on. In case of higher flow rate of 0.0225kg/s, this much of heat input is insufficient to heat the heat transfer fluid from room temperature to the required temperature, thereby heat transferred to the phase change material becomes lower. The flow rate of 0.02kg/s indicated best among the other flow rates used, because all the above explained losses are optimized at this flow rate.

4. Conclusion

The performance analysis of the developed latent heat thermal energy storage system with sodium thiosulfate pentahydrate as phase change material was investigated experimentally in the current study. As the energy analysis was inadequate for the performance evaluation of the developed system, exergy analysis was also done. And also the variation of energy efficiency and exergy efficiency of storage unit with heat flux and mass flow rate was examined. When compared to energy efficiency, the exergy efficiency of the system was found to be very low. The results from the observations and calculations clearly show that the exergy efficiency of the latent heat thermal energy storage system is very low. Entropy generation within the system reduces its exergy efficiency.

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